Table 1.—Summary of dissolved solids in Paleozoic aquifers and confining layers

**GROUND-WATER FLOW SYSTEMS** 

could be brine like the clusters of points. The map has question marks

**EXPLANATION** 

**EXPLANATION** 

The potentiometric surface maps represent an average surface where these interpretations seemed most speculative. [Dissolved solids: Number of samples, total number of samples used in the analysis is on top and the number of samples from the Middle Paleozoic Aquifers Upper Paleozoic Aquifers WATSTORE file and the BRINE file are given below as W/B; geometric mean, mean of the log transformed values, which is generally closer to the median than an arithmetic mean; Box plot of distribution: when the data from the two files are significantly Baars, D. L., 1962, Permian system of Colorado plateau: American based on data collected over a period of about 30 years (1954–1984). Association of Petroleum Geologists Bulletin, v. 46, no. 2, and confining layers unit MIDDLE PALEOZOIC AQUIFERS UNIT The scarcity of data in some areas made the averaging necessary, different they are separated and indicated by (W) for WATSTORE and (B) for BRINE files; The scale is logarithmic so that 2 equals Exposed p. 149-218. because data were collected at different times and in different parts of Water samples from the Madison Limestone, the Leadville 100, 3 equals 1,000, 4 equals 10,000, and 5 equals 100,000. Ticks on the logarithmic scale indicate tenths of log units, thus a value Eugster, H. P., and Hardie, L. A., 1978, Saline lakes, in Lerman, A., ed., Concealed beneath younger Concealed beneath younger at 3.4 would be about 2,500 mg/L. +, median value; < >, confidence interval around the median for comparison among aquifer units; the study area. The surface may reflect the effects of oil and gas Limestone, the Redwall Limestone, the Deseret Limestone, the Ouray Lakes—Chemistry, geology, physics: New York, Springer-Verlag, | |, 25 and 75 percent quartiles of the data, that is, 50 percent of the values are within the two vertical lines (these lines are rocks occurrence and development (which could include some groundwater Limestone, the Humbug Formation, the Chaffee Formation, undif-Concealed beneath olde sometimes covered by the confidence interval signs); ---- , range of the data values that are not considered extreme; \*, data value considered as an extreme value, called "outside" values, (if more than one occurs at a point, the number of samples at the Concealed beneath older p. 237-293. ferentiated Mississippian rocks, and undifferentiated Devonian rocks withdrawal as part of the oil and gas removal process) in some areas, Geldon, A. L., 1985, Hydrogeology of northwestern Colorado, with rocks particularly in extreme southeastern Utah, northwestern Colorado, were combined to make the map showing dissolved-solids concentrations point is used as the symbol); o, data value considered to be very extreme, called "far outside" values; x, individual data point results of aquifer tests at Glenwood Springs, in Pearl, R. H., ed., where no box plot is given. See text for additional explanation. See figure 2 for location of tectonic features in the study area.] (fig. 13) for the middle Paleozoic aquifer unit. The majority of the and along the northeastern boundary of the study area in Wyoming. In Water and energy resources of west-central Colorado: Colorado samples are from Mississippian carbonate rocks. a few scattered areas, ground water is withdrawn for irrigation or public Limit of middle Paleozoic Ground Water Association 4th annual field trip guidebook, p. 33–41. Limit of upper Paleozoic Dissolved solids (in mg/L) supply. Many of these withdrawals are from shallow alluvial aquifers Comparison of figures 11 and 13 indicates that recharge areas aquifers unit—Dashed aquifers and confining Hintze, L. F., 1973, Geologic history of Utah: Provo, Utah, Brigham along the larger rivers; Paleozoic rocks are too deeply buried, and (or) coincide with areas of small dissolved-solids concentration, presumably where approximately layers unit—Dashed Location of Young University Geology Studies, v. 20, pt. 3, 181 p. Box plot of distribution located their water quality is too poor over much of the study area for them to because all recharge in the study area is in the form of precipitation that where approximately samples within \_1980, Geologic map of Utah: Utah Geological and Mineral tectonic features ber Comments Potentiometric contour aquifer have been extensively developed for supply. is low in dissolved solids. Near areas of outcrop, the middle Paleozoic of metric Less 100 Survey map, scale 1:500,000, 2 sheets. Shows altitude at which of study region unit contains water of a calcium bicarbonate type, with dissolved-solids Potentiometric contour-Kent, H. C., and Porter, K. W., eds., 1980, Colorado geology: Denver, water level would have 1,000 10,000 100,000 100,000 Shows altitude at which MIDDLE PALEOZOIC AQUIFERS UNIT concentration of less than 1,000 mg/L. As the water travels through stood in tightly cased wells. Rocky Mountain Association of Geologists, 258 p. water level would have the system, however, the concentration of dissolved solids increases. Dashed where approxi-The source of ground water recharge in the study area is stood in tightly cased wells King, P. B., and Beikman, H. M., 1974(1975), Geologic map of the Where the formations are buried, the ground water is slightly to mately located. Queried precipitation (Price and Arnow, 1974, p. C9). Recharge areas for the Permian Distributed These are values that could Dashed where approxi-United States, exclusive of Alaska and Hawaii: U.S. Geological -----|<+> |----where implied. Contour throughout the moderately saline (from 1,000 to 100,000 mg/L dissolved solids) and only be identified by age. middle Paleozoic aquifers are the Defiance, Uinta, Uncompangre, San mately located. Queried Survey Special Geological Map, scale 1:2,500,000, 3 sheets. interval, in feet, is variable. study area and not by major aquifer where implied. Hachures Juan, White River, and Park Range uplifts, the Sierra Madre, the San predominantly of a sodium chloride type. Brine (dissolved-solids undiffer Datum is sea level Knight, R. L., and Cooper, J. C., 1955, Suggested changes in Devonian indicate depression in Rafael swell, and the Overthrust Belt. Normal annual precipitation may concentrations greater than 100,000 mg/L) is present in a large part of entiated -- Boundary of study area terminology of the four corners area, in Geology of parts of potentiometric surface. this hydrogeologic unit in the Uinta, Piceance, and Paradox basins. The exceed 20 in. over these areas providing water to recharge the exposed Contour interval, in feet, is Kaibab San Rafael swell Paradox, Black Mesa, and San Juan basins: Four Corners No significant difference Paleozoic rocks. Potentiometric contours indicate that recharge brine is also predominantly of sodium-chloride type. In the Paradox Contact—Dashed where variable. Datum is sea Geological Society Guidebook, 5th Field Conference, p. 56-58. Limestone among the two data sources. probably occurs through Mesozoic rocks on the northern side of the basin, dissolved-solids concentrations in excess of 300,000 mg/L are approximately located Far outside value of 505 mg/L Lines, G. C., and Glass, W. R., 1975, Water resources of the thrust belt reported. These concentrations probably result from the dissolution of --- Boundary of study area Uncompangre uplift. On the southern side of the uplift, faulting has CARBO is from WATSTORE. of western Wyoming: U.S. Geological Survey Hydrologic Investigasalts in the overlying Pennsylvanian Hermosa Formation. buried Paleozoic rocks too deeply for them to be recharged to any tions Atlas HA-539, scale 1:250,000, 3 sheets. Contact—Dashed where Minimum and maximum values significant extent through overlying rocks. approximately located are both from WATSTORE. Love, J. D., 1950, Paleozoic rocks on the southwest flank of the Wind UPPER PALEOZOIC AQUIFERS AND CONFINING LAYERS UNIT Ground-water flow through the study area generally is toward the Large range in the data may reflect the change from stone River Mountains, near Pinedale, Wyoming: Wyoming Geological southwest, although the flow appears to be diverted around the Uinta Upper Paleozoic confining layers subunit Association Guidebook, Fifth Annual Field Conference, Southwest and Uncompangre uplifts where middle Paleozoic aquifers are absent recharge areas to deep basins. Data in figure 14 present dissolved-solids concentrations of water (fig. 11). Further investigation is needed to determine whether this is in confining layers that are associated with the Paradox basin evaporite San Rafael swell Highest concentration of Love, J. D., Christiansen, A. C., Bown, T. M., and Earle, J. L., compilers, ---< +> |----indeed the case; calculations based on the slope of the aquifers and the minerals (fig. 5; table 1). Over one-half of the 57 samples are from the 17,700 from BRINE, next 1979, Preliminary geologic map of the Thermopolis 1° x 2° large dissolved-solids concentrations suggest that ground water in the Mountain basin Paradox Member of the Hermosa Formation, and most of the others highest concentration is quadrangle, central Wyoming: U.S. Geological Survey Open-File Member of 6,040 mg/L. deeply buried Mississippian formations in the Uinta, Piceance, and are from the other members of the Hermosa Formation. Brine is Report 79-962, scale 1:250,000. Paradox basins may be virtually stagnant (E. J. Weiss, U.S. Geological present in these formations, with concentrations in excess of Formation Love, J. D., Weitz, J. L., and Hose, R. K., 1955, Geologic map of Survey, oral commun., 1983). The middle Paleozoic aguifers discharge 300,000 mg/L. The brines are supersaturated with respect to halite Wyoming: U.S. Geological Survey map, scale 1:500,000, 2 to the valleys of the Colorado and Green Rivers and their tributaries De Chelly Defiance uplift Samples are mostly from (NaCl), and calcium dominates over sodium in some of these brines. and to springs in areas where the aquifers are exposed, such as the recharge areas. Chloride is the dominant anion. In contrast to the midddle Paleozoic MacLachlan, M. E., 1981, Stratigraphic correlation chart for western eastern edge of the Uinta uplift and the White River uplift. Reported aquifers unit, zones with dissolved-solids concentrations of less than Colorado and northwestern New Mexico: Socorro, New Mexico, discharges of springs and wells near Glenwood Springs, Colo., range 10,000 mg/L are rare. The greater salinity reflects the lithology of the Geological Society Guidebook, 32nd Field Conference, p. 75–79. from less than 5 to 2,700 gal/min (Geldon, 1985; Teller and Welder, Uinta basin and beds containing evaporite minerals; greater salinity also reflects the The differences among the two \_\_\_1984, General geology of the Piceance basin, in Taylor, O.J., Sandstone uplift sources of data are evident. restricted flow of water. compiler, U.S. Geological Survey Professional Paper 1310 (in Most BRINE samples are Upper Paleozoic aquifers subunit from greater depths in the UPPER PALEOZOIC AQUIFERS AND CONFINING LAYERS UNIT Uinta Basin and reflect a Miesch, A. T., 1967, Methods of computation for estimating geochemical Although a large number of samples were from formations that are ----- (+ > |-Upper Paleozoic confining layers subunit real change of abundance: U.S. Geological Survey Professional Paper 574-B, 15 p. part of the upper Paleozoic aquifers subunit, information on specific centrations with depth Permeability in the confining layers subunit ranges from one to Molenaar, C. M., and Halvorsen, D. U., 1969, Nomenclature chart of (see figure 15.) geologic formations was scarce except in localized areas. The only three orders of magnitude less than in the overlying aquifers (A. L. the Grand Canyon and adjacent areas, in Four Corners Geological formations used in the map were the Weber Sandstone of Early Tensleep Green River basin 60 6,220 Geldon, U.S. Geological Survey, written commun., 1984), and it is The low outside value is the Society Guidebook, 5th Field Conference, p. 68. Permian and Late Pennsylvanian age, the Coconino Sandstone, the Sandstone | and Wind River \* -----|<+> |--one WATSTORE sample. unclear whether or not a regional flow system exists in these Price, Don, and Arnow, Ted, 1974, Summary appraisals of the Nation's Cedar Mesa and White Rim Sandstone Members of the Cutler Formation, Remaining samples are from or formations. Therefore, construction of a potentiometric surface map groundwater resources—Upper Colorado Region: U.S. Geological and gas drilling and reflect and the De Chelly Sandstone (fig. 15). These sandstones are of for this subunit was not attempted. the dissolved solids of water Survey Professional Paper 813-C, 40 p. Permian age. Near areas of outcrop, water in the subunit exhibits large in the deeper basins rather Rocky Mountain Association of Geologists, 1972, Geologic Atlas of Upper Paleozoic aquifers subunit changes in quality over small distances. This is most noticeable in the than in the recharge areas. the Rocky Mountain region: Denver, 331 p. Uinta basin and around the White River uplift. Where these Permian The only source of recharge for the upper Paleozoic aquifers Samples are from recharge Stiff, H. A., Jr., 1951, The interpretation of chemical water analysis by subunit, as for the underlying middle Paleozoic aquifers unit, is sandstones are recharged, along the southern flank of the Uinta uplift, ------<+>!-- \* areas and do not reflect means of patterns: Journal of Petroleum Technology, v. 3, p. 15-17. the San Rafael swell, and the Defiance uplift, the water is a calcium precipitation. Topography strongly controls ground-water flow direction deep circulation. Taylor, O. J., Hood, J. W., and Zimmerman, E. A., 1983, Plan of study bicarbonate type. (Note that the map unit in figure 15 is composed of in the aquifers that make up the upper part of the subunit; groundfor the Regional Aquifer Systems Analysis of the Upper Colorado water flow follows generalized surface drainage (fig. 12). Dissolvedonly Permian sandstones. The subunit mapped in figure 12 is more River Basin in Colorado, Utah, Wyoming, and Arizona: U.S. extensive, and hence, is recharged in different places.) Where the solids concentrations in the upper Paleozoic aquifers subunit is not Formation Geological Survey Water-Resources Investigations Report great enough to significantly affect water density, so the altitude of the subunit is deeper, the water is more saline, and the water type changes 83-4184, 23 p. Cutler Henry Mountains, water level in a tightly-cased well tapping this subunit should be similar from calcium bicarbonate to sodium bicarbonate. There are few The ranges of Culter and Formation | Monument uplift \_1984, Hydrogeologic framework of the Upper Colorado Halgaito are nearly equal to that shown in figure 12. samples of water from this unit in some of the deep basins. However, with the ---(+)----River Basin in Colorado River Basin in Colorado, Utah, Wyoming, Natural recharge to the upper Paleozoic aquifers subunit occurs the samples indicate that the dissolved-solids concentration exceeds Halgaito and Arizona: U.S. Geological Survey Hydrologic Investigations around the edges of the study area in the High Plateaus and Wasatch 35,000 mg/L and in some areas may exceed 100,000 mg/L. Note that Plateau, the Overthrust Belt, the Uncompangre, Uinta, and White River Atlas HA-687. the intervals for dissolved-solids concentration in figure 15 are White River uplift Teller, R. W., and Chafin, D. T., 1984, Selected drill-stem test data from BRINE sample (38,300 mg/L) uplifts, and the San Rafael swell. Discharge is principally to the different from those used on the other two dissolved-solids maps, the Upper Colorado River Basin: U.S. Geological Survey Wateris from a depth of about 8,700 Colorado and Green Rivers and their tributaries. In particular, the because the overall range of concentrations is smaller. The change in feet. The others are near Resources Investigations Report 84–4146. effect of the Colorado River on the potentiometric surface downstream concentration intervals provides additional detail. the surface. Teller, R. W., and Welder, F. A., 1983, Ground-water potential of the from the Uncompangre uplift and of the White and Yampa Rivers in Leadville Limestone on the White River uplift in Garfield and Rio the northern Piceance basin is pronounced. The subunit is unconfined Four Corners Blanco Counties, Colorado: U.S. Geological Survey Water-These few samples have a in many areas, the largest of which are the Monument and White River Formation platform **SUMMARY** range greater than Resources Investigations Report 83–4036, 28 p. uplifts. Depressions in the potentiometric surface northeast of Tweto, Ogden, 1979, Geologic map of Colorado: U.S. Geological Monticello, Utah, and on both sides of the San Juan River in Utah and No information on depth of divided into four hydrogeologic units; sufficient data to perform Survey map, scale 1:500,000, 2 sheets. the samples. Arizona are probably related to oil and gas occurrence and development. Velleman, P. F., and Hoaglin, D. C., 1981, Applications, basics, and regional analyses are available for only the middle Paleozoic aquifers unit and the upper Paleozoic aquifers and confining layers unit. The computing of exploratory data analysis: Boston, Massachusetts, WATSTORE samples (200 mg/L) structure of these hydrogeologic units is influenced by numerous Duxbury Press, 354 p. are far lower than BRINE sam-**GROUND-WATER CHEMISTRY** Weir, J. E., Maxfield, E. B., and Hart, I. M., 1983, Reconnaissance of the Uinta uplift basins and uplifts; both depth-to-top and thickness are generally ples which range up to The data presented in table 1 represent all of the data available for geohydrology of the Moab-Monticello area, western Paradox 100,000 mg/L. Very concengreater in basins than uplifts. Potentiometric maps indicate that water trated samples are from oil the various Paleozoic aquifers and confining layers. For some in these two hydrogeologic units generally moves from topographically Basin, Grand and San Juan Counties, Utah: U.S. Geological fields in Wyoming. hydrogeologic units, it was possible to combine data and present the high areas to discharge in the valleys of the Colorado and Green Rivers Survey Water-Resources Investigations Report 83–4098, 59 p. V Darwin Green River basin 2 10,100 geographic variations in dissolved-solids concentration on maps. Both samples from the same and their tributaries and to springs. Wengerd, S. A., and Strickland, J. W., 1954, Pennsylvanian stratigraphy well at depths of about 6,725 Contours of the data were fit by hand. Where there were few data, The aquifers of Paleozoic age contain water with a dissolved-solids ARRIBI of Paradox Salt basin, Four Corners region, Colorado and Utah n Member of feet and 6,800 feet. geologic setting of the hydrogeologic unit was used to infer the concentration ranging from less than 50 mg/L to greater than American Association of Petroleum Geologists Bulletin, v. 38, no. i Amsden approximate dissolved-solids concentration. For example, there are a Formation 400,000 mg/L. Large areas that contain brine are present in the 10, p. 2157–2199; Correction, v. 39, no. 2, p. 259, 1955. few data points for the middle Paleozoic aquifers in the White River confining layers of Early Pennsylvanian age and also in the aquifers of Williams, P. L., and Hackman, R. J., 1971, Geology, structure, and uplift. The aquifer crops out in an area with abundant precipitation; Mississippian and Devonian age. Both the upper Paleozoic age uranium deposits of the Salina quadrangle, Utah: U.S. Geological therefore, near the outcrops the aquifers are assumed to have low sandstones and the middle Paleozoic aquifers unit contain fresh water Survey Miscellaneous Geologic Investigations Map I-591, scale Samples are low in dissolved dissolved-solids concentrations. Data for the middle Paleozoic aquifers Formation uplift where recharged, but the occurrence of evaporite minerals and 1:250,000, 2 sheets. AREA EXCLUDED solids considering some are in the Uinta basin are clustered, making the interpretations between Wilson, E. D., and Moore, R. T., 1969, Geologic map of Arizona: from about 6,000 feet deep. restricted ground-water flow causes the fresh water to grade into very clusters of data difficult. However, the great depth of the middle saline water at depth. Occurrence of evaporite minerals and restricted Arizona Bureau of Mines and U.S. Geological Survey map, scale Paleozoic aquifers in this basin suggests that all the water at depth ground-water flow are the major causes of the high salinities. 100 KILOMETERS 1:500,000, 1 sheet. 100 KILOMETERS Yampa plateau and 16 3,460 Distinction among the two i phoria Great Divide 6/10 data sources. The far outa Formation basin side value (276,000 mg/L) Figure 11.—Potentiometric surface of middle Paleozoic aquifers unit. Figure 12.—Potentiometric surface of upper Paleozoic aquifers subunit. from the BRINE file is from the Green River Basin **EXPLANATION** EXPLANATION at a depth of 12,700 feet. Dissolved solids concentra-Dissolved solids concentration in milligrams per Hermosa Henry Mountain WATSTORE samples range from liter and water-quality tion in milligrams per Formation basin and Monusprings in recharge areas to liter and water-quality ment uplift deep wells with brines. The Less than 1000; fresh Less than 1000; fresh both data sources is very 1000 to 3000; brackish 1000 to 10,000; slightly 3000 to 10,000; slightly 10,000 to 100,000; mody Paradox Four Corners The low outside and far out-1 Member of platform, east 19/21 erately to very saline \*\*----| < +|> side values are from more 10,000 to 35,000; moder v Hermosa central Utah shallow intervals than mos 100,000 to 300,000; brine a Formation other samples. The BRINE Greater than 35,000; very samples come from zones Greater than 300,000 saline to brine where salt dissolution has Colored area terminates without a clearly defined boundary a clearly defined boundary where insufficient data are Amsden Green River basin 3 12,640 All three samples are from where insufficient data ar available to extend Formation the same well. The concenavailable to extend tration increases with depth Line of equal dissolved solids - Line of equal dissolved solids content—Dashed where content—Dashed where approximately located. Missis- Distributed Includes samples from reapproximately located Queried where implied. sippian throughout the charge areas (low outside Queried where implied. Interval, in milligrams per undiffer- study area values). The majority of Interval, in milligrams per liter, is variable samples reflect concenliter, is variable --- Boundary of drainage area tration at depth in many --- Boundary of drainage area Boundary of areas where S Madison San Rafael swell, 26 8 980 Boundary of areas where Range is similar to the range geologic unit is absent— Dashed where approxi-00 \* ---<+>!--- \*\* 0 Group or | Uinta uplift and of the Leadville limestone. geologic unit is absent-Dashed where approxi-Limestone basin, and Great Low outside values are from mate. Queried where Divide basin mate. Queried where springs in recharge areas. No implied significant difference among --- Boundary of study area CARBO data from two sources. - · · · Boundary of study area Water types, Stiff diagrams Middle P Redwall San Rafael swell Large range in the data. Water types, Stiff diagrams (Stiff, 1951)—Color cor-Limestone and Henry (Stiff, 1951)-Color corresponds to the dissolved Mountain basin is from about 8,100 feet. responds to the dissolved solids scale above. Number solids scale above. Number above diagrams is the dis-Two high outside values are above diagrams is the dis-Limestone to Four Corners from BRINE file. The large of sample. The line from range in data reflects the of sample. The line from the diagram to the map changes from recharge to the diagram to the map indicates the location of deep basins. indicates the location of the sample the sample 9 | 44.000 (W) e Devonian Henry Mountains only be identified by age, o entiated but not by major aquifer. Large range may be due to Sulfate (SO<sub>4</sub>) variation from recharge to Lower r Ordo-Paleo- d vician Samples are from the same well. This shows the large zoic o undiffer-aquifers v entiated variability that can exist with depth. Bighorn Green River basin Range is from near 250 mg/L Dolomoite (two WATSTORE samples) to 31,600 mg/L (a BRINE file sample at 15,200 feet). Cambrian Green River basin, 14 11.400 Large range in the data, but undiffer- Great Divide most samples are of moderateentiated basin, Uinta ly saline water. No specific aquifer could be identified a Sawatch White River reflects water in recharge volcanic field aquifers i Flathead Wind River uplift 3 9,050 Samples depths are from 5,800 to 7,800 feet. The difference among these sample and those of the Sawatch Sandstone reflect changes with depth for this basal Cambrian P Precam- San Juan volcanic 20 r brian field, Most samples are from springs e undiffer- Central Colorado in areas of outcrop. entiated aquifers b Mountain r Group Reflects local circulation i unreactive rock. n Formation **CONVERSION FACTORS** The inch-pound units used in this report may be converted to metric (SI) units by use of the following conversion factors: gallon per minute inch (in.) 1.609 square mile (mi<sup>2</sup>) FROM STUDY To convert degree Fahrenheit (°F) to degree Celsius (°C) use the following formula: °C=5/9(°F-32). To convert degree Celsius (°C) to degree Fahrenheit (°F) use the following formula: °F=(°Cx9/5)+32. The following term and abbreviation also is used in this report: milligram per liter (mg/L). Figure 13.—Dissolved-solids concentration in middle Paleozoic aquifers unit, Figure 14.—Dissolved-solids concentration in upper Paleozoic confining layers subunit. Figure 15.—Dissolved-solids concentration in upper Paleozoic aquifers subunit INTERIOR—GEOLOGICAL SURVEY, RESTON, VA-1989

SELECTED REFERENCES